USAARL Report No. 2017-14

Understanding of a Key Aspect of Situation Awareness: A Research and Development Agenda to Refine the Model of Spatial Orientation

By Ben D. Lawson[1], Henry P. Williams[2], Michael C. Newman[3], Braden J. McGrath[4], Angus H. Rupert[1]

[1]U.S. Army Aeromedical Research Laboratory
[2]Naval Aerospace Medical Research Unit – Dayton
[3]National AeroSpace Training and Research Center
[4]Engineering Acoustics, Inc.

United States Army Aeromedical Research Laboratory

Auditory Protection and Performance Division
Aircrew Health and Performance Division

July 2017

Approved for public release; distribution unlimited.

Notice

Qualified Requesters

Qualified requesters may obtain copies from the Defense Technical Information Center (DTIC), Fort Belvoir, Virginia 22060. Orders will be expedited if placed through the librarian or other person designated to request documents from DTIC.

Change of Address

Organizations receiving reports from the U.S. Army Aeromedical Research Laboratory on automatic mailing lists should confirm correct address when corresponding about laboratory reports.

Disposition

Destroy this document when it is no longer needed. Do not return it to the originator.

Disclaimer

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Citation of trade names in this report does not constitute an official Department of the Army endorsement or approval of the use of such commercial items.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: 10-07-2017

2. REPORT TYPE: Final

3. DATES COVERED *(From - To)*:

4. TITLE AND SUBTITLE

Understanding of a Key Aspect of Situation Awareness: a Research and Development Agenda to Refine the Model of Spatial Orientation

5a. CONTRACT NUMBER: N/A

5b. GRANT NUMBER: N/A

5c. PROGRAM ELEMENT NUMBER: N/A

5d. PROJECT NUMBER: N/A

5e. TASK NUMBER: N/A

5f. WORK UNIT NUMBER: N/A

6. AUTHOR(S)

Lawson, Ben D.
Williams, Henry P.
Newman, Michael C.
McGrath, Braden J.
Rupert, Angus H.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Aeromedical Research Laboratory
P.O. Box 620577
Fort Rucker, AL 36362

8. PERFORMING ORGANIZATION REPORT NUMBER: USAARL 2017-14

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Program Executive Office Aviation

Defense Health Program Joint Program Committee Aviation Mishap Prevention
1077 Patchel Street
Fort Detrick, MD 214702-5024

10. SPONSOR/MONITOR'S ACRONYM(S): PEO Aviation; DHP JPC AMP

11. SPONSOR/MONITOR'S REPORT NUMBER(S): N/A

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Loss of situation awareness (LSA) occurs when pilots are not attending to their instruments, due to factors such as workload or distraction. A deadly aspect of LSA is spatial disorientation, which usually occurs during flight in degraded visual environments when the forces on the pilots' bodies are misleading concerning the direction of the true gravitational vertical. A mathematical model has been developed to predict human orientation and motion perceptions, based on factors such as the moment-by-moment angular and linear accelerations of one's body. The model has been applied to the evaluation of suspected spatial disorientation mishaps. This report represents an expert committee summary of the key knowledge gaps that should be filled to mature the model. Gaps are identified where research is needed to provide data for the model or to refine it to be more accurate. The committee identified the key publications whose findings would need to be incorporated into a fully mature model of human orientation. The committee also considered the key psychophysical measures of orientation perception needed to further validate the model.

15. SUBJECT TERMS

spatial disorientation, vestibular, motion perception, self-motion, orientation model, movement control, balance, aviation safety, sensorimotor, sensory integration, degraded visual environment

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLAS	UNCLAS	UNCLAS	SAR	39	Loraine St. Onge, PhD

19b. TELEPHONE NUMBER *(Include area code)*: 334-255-6906

This page is intentionally blank.

Acknowledgements

The authors thank the following sponsors for supporting past or current aspects of this work:

- U.S. Army Medical Research and Materiel Command (USAMRMC; In-House Laboratory Independent Research), for supporting the initial model development for military applications by authors Newman, Lawson, and Rupert.
- Small Business Innovative Research program (Program Executive Office [PEO] for Aviation), for their support of the meeting described in this report and for aiding the efforts of authors McGrath and Newman to transition the model.
- The Defense Health Program, Joint Program Committee-5 ([JPC-5] Aviation Mishap Prevention [AMP]), for their support of the participation of Drs. Williams, Lawson, and others in the discussions summarized in this report, and for support of follow-on studies to test and refine the model.
- The authors thank Drs. Torin Clark, Kara Beaton, William Ercoline, Bruce Wright, and Gary Zets, for their participation and input during the discussions leading to this report. The authors thank Ms. Deahndra Grigley, Ms. Linda-Brooke Thompson, Mr. Jared Basso, Ms. Melissa Ginn, Mr. Casey Harris, and Ms. Lana Milam, for their assistance with the meetings and this report derived from them.
- This effort was supported in part by personnel appointed to the Research Participation Program at USAARL, administered by the Oak Ridge Institute for Science and Education through and interagency agreement between the U.S. Department of Energy, USAMRMC, and USAARL.

This page is intentionally blank.

Table of Contents

List of Tables

Appendices

This page is intentionally blank.

Introduction

Loss of situation awareness (LSA) is an important contributor to human-error mishaps in aviation and other domains. Loss of situation awareness occurs when one's perception or comprehension of the environment or significant events is inaccurate. The most common type of LSA is Level I LSA, i.e., the failure to perceive the information needed to maintain accurate situation awareness (Endsley, 1995). For example, when a pilot is in a banking turn, the resultant forces on the aircraft are roughly aligned with the pilot's torso, causing an illusion of straight-and-level flight, especially during distraction from the attitude indicator.

Aviation spatial disorientation (SD) can be described as a pilot's inaccurate perception of the altitude, position, or motion of his/her aircraft relative to the Earth's surface or other points of reference (Benson, 1989). Spatial disorientation typically (but not always) occurs within some form of degraded visual environment (DVE) such as flight under instrument conditions or at night (Gibb, Gray, & Scharff, 2010). If not recognized and resolved quickly, this misperception can cause controlled flight into the ground, midair collision, or inappropriate control inputs. The prevalence of this problem has been documented by mishap reports and surveys indicating that nearly all pilots experience some form of SD during their careers (Braithwaite, Durnford, Crowley, Rosado, & Albano, 1998; Singh & Navathe, 1994; Tormes & Guedry, 1975). Accident statistics help quantify the size and severity of this deadly threat to aviation safety. Poisson and Miller (2014) reviewed mishap data from the United States Air Force (USAF) Safety Center's Air Force Safety Automated System (AFSAS). This review evaluated the 21 year period from Fiscal Years 1993 through 2013, and it focused upon Class A mishaps, which resulted in a loss of life and/or more than $2 million in property damage. The authors found a total of 601 Class A mishaps, and 72 (12%) of these included SD as a causal factor. Tragically, there were 101 lives lost in those 72 mishaps. When fatality rates of non-SD and SD-related Class A's were compared, it was found that 16.1% of non-SD mishaps involved a fatality, but 61.1% of the SD-related mishaps were fatal.

Spatial disorientation is a problem for the Army and Navy as well. In a study of the U.S. Army, Braithwaite, DeRoche, Avarez, and Reese (1997) reported that between 1987 and 1995, there were 970 Class A through C mishaps. Of these, 291 (30%) involved SD and claimed 110 lives. A more recent U.S. Army Combat Readiness Center review of fiscal 2002 through fiscal 2013 data showed that DVE was a key factor in 25% of Class A/B mishaps, with DVE mishaps accounting for 46% of total fatalities (Edens & Higginbotham, 2014). Flying in a DVE with a correct mental model of one's orientation and motion would not be hazardous, but it becomes hazardous when improper control inputs are made because an accurate mental model of what is happening in time and space is lost, for example, due to SD. The U.S. Naval Safety Center indicates that SD was designated the top aeromedical causal factor of Class A mishaps occurring from 1990 – 2008 (Gibb, Ercoline, & Scharff, 2011).

In the huge general aviation (GA) community, SD has been cited as a causal factor in 11% to 16% of all fatal accidents (Collins & Dollar, 1996; Kirknum, Collins, Grape, Simpson, & Wallace, 1978). In GA accidents that were attributed to SD, the chances of survival were alarmingly low, with 90% of the studied cases involving fatality. Similarly, Mortimer (1995) found 92% of GA SD accidents to be fatal.

Loss of control inflight (LOC-I) and controlled flight into terrain (CFIT) are frequently mentioned commercial aviation problems that are strongly associated with SD (Veronneau & Evans, 2004; Lawson, Smith, Kass, Kennedy, & Muth, 2003). A report from Boeing (2014) listed LOC-I and CFIT as the top two causes of fatalities in the worldwide commercial jet fleet (of any manufacturer) in the period covered from 2004 through 2013. The total number of lives lost in the 16 LOC-I and 16 CFIT accidents was a staggering 2,380.

Clearly, SD is a threat to safety in the military, general, and commercial aviation communities. Traditional approaches to combatting SD have focused on training, ranging from simple demonstrations in a Bárány chair to sophisticated motion-based flight simulators, to training in actual aircraft in simulated instrument flight conditions. Other methods of reducing SD incidence have concentrated on novel visual instrument design. While these approaches certainly have merit, the fact that the SD mishap rate is not decreasing (Gibb, Ercoline, & Scharff, 2011) any further suggests that other strategies should be considered. Our approach is to gain a better understanding of the root causes of SD and to foster the development and validation of models that can simulate and predict SD during a wide variety of relevant stimulus situations known to occur in flight. This can aid greatly with mishap analysis and mishap-prevention training.

We have recommended that mishap evaluations should not simply link a mishap to a possible SD illusion logically and qualitatively, but instead should be more quantitative, comprehensive, and evidence-based (Newman, Lawson, Rupert, & McGrath, 2012). A better approach to inferring SD as a mishap contributor entails matching data streams from the on-board recorders (e.g., acceleration, pilot control inputs) against scientific, quantitative models of SD to determine if SD would occur. The flight parameter data provide the force vectors experienced by the aircrew prior to the mishap. The existing SD models use vector analysis to exploit this information and knowledge of perceptual functioning from basic science (e.g., dynamics of vestibular and somatosensory responses) to model what the pilot would have perceived if he/she was not adequately attending to veridical orientation cues from the aircraft attitude instruments or outside visual cues.

We developed a mathematical model of orientation to aid in the processing, simulation, and visualization of human perception in response to three-dimensional, complex, multisensory motion stimuli (Newman et al., 2012; Newman, Lawson, McGrath & Rupert, 2014; Newman et al., 2016). The model has already been used successfully to reproduce human perceptual responses to more than a dozen laboratory motion perceptions and spatial disorientation illusions, including an F/A-18 mishap and the disorienting and disturbing Coriolis cross-coupling sensations associated with certain motion profiles aboard advanced centrifuge-like devices such as the new Disorientation Research Device (Newman et al., 2012). Moreover, our model (and six other perception models) were programmed into a prototype software algorithm to facilitate comparison with previous research and modeling results as well as our predictions.

In our model, three-dimensional vectors of linear acceleration and angular velocity are provided to the vestibular system model in a head-fixed coordinate frame (Newman et al., 2016). Angular velocity is integrated using a quaternion integrator to keep track of the orientation of gravity with respect to the head. The otolith transfer functions are modeled as unity and respond to the gravitoinertial force. The semicircular canals (SCC) are modeled as second-order high-pass filters with a cupula-endolymph long time constant of 5.7 seconds (s) and a neural adaptation time constant of 80 s. Vestibular information is combined with visual input from up to four visual cues; these include: visual position, visual velocity, visual angular velocity, and visual gravity/orientation. The above inputs must then be integrated. Afferent signals from the semicircular canals, otoliths, and visual sensors are compared in the central nervous system "Observer" portion of the model against expected values from a similar set of internal sensory dynamics based on the literature. The resultant error signals are weighted with nine free parameters weighing various aspects of vestibular angular velocity and linear acceleration, visual position, orientation, linear velocity, and angular velocity, the gravitoinertial force and its influence on the angular velocity estimate, and the total estimate of angular velocity. The model outputs are central estimates of perceived linear acceleration, gravity, angular velocity, linear velocity, and position.

Approach

- As part of a Small Business Innovative Research effort and a Defense Health Program Joint Program Committee project, a group of orientation experts were consulted to determine how best to improve the existing orientation model. Three rounds of meetings were held:
    - The first was a small two-day in-person meeting at Fort Rucker, AL, in January of 2015 (Appendix A). It was attended by small team of spatial orientation mathematical modeling specialists and orientation experts who had participated in projects on quantitative orientation modeling.
    - The second meeting was a teleconference in March of 2015, which included some additional spatial disorientation experts from the aeromedical domain. This meeting was held to ensure operational relevancy and add any missing elements from the first meeting.
    - The third meeting was staged as a larger in-person two-day workshop at the Institute of Human and Machine Cognition in Pensacola, FL, in January of 2017.
- This report describes the committee recommendations from the first two meetings (Table 1).
    - The third meeting of a larger group of experts included many formal presentations and a raw proceedings transcript of more than 700 pages. This third meeting will be discussed separately in an upcoming publication.
- In the first two meetings, the orientation experts were tasked with defining a research and development agenda for refinement of the existing explanatory mathematical model of human spatial orientation perception. Therefore, discussion topics at the first two meetings included:
    - Identifying gaps in current orientation model data or accuracy of the model.
    - Agreeing on the key literature on orientation perception containing methods or constraints relevant to the model and data for which the model must account.
    - Considering the options for psychophysical measures needed to inform and validate the model.

- The group findings concerning these various topics are described in the next section of this report.

Table 1. Spatial orientation and orientation modeling experts providing feedback.[1]

Name	Title	Affiliation
Angus Rupert, M.D., Ph.D.	Medical Research Scientist	USAARL
Ben Lawson, Ph.D.	Research Psychologist	USAARL[2]
William Ercoline, Ph.D.	Senior Manager/Scientist	Wyle Science Technology & Engineering
Braden McGrath, Ph.D.	Vice President of Strategy & Development	Engineering Acoustics, Inc.[3]
Henry Williams, Ph.D.	Research Psychologist	Naval Medical Research Unit Dayton
Kara Beaton, Ph.D.	Research Engineer	NASA Johnson Space Center[4]
Mike Newman, M.S.	Research Scientist	National AeroSpace Training & Research Center
Torin Clark, PhD.	Assistant Professor	University of Colorado, Boulder

Findings

The orientation experts discussed the most important ways to improve the orientation model. They identified the perceptual phenomena accounted for by the model, the relevant phenomena yet to be accounted for, and the top-five knowledge gaps that need to be filled by further research to mature the orientation model for its intended uses. They also discussed optimal approaches to the measurement of orientation perception in future studies seeking to gather data in a form the model can readily digest and incorporate in order to render improved simulations. Finally, the experts identified the key literature on human spatial orientation perception for which a fully mature model should eventually be able to account for. These committee findings are elucidated in this report. Many of the findings and recommendations are summarized immediately below, but a few require lengthy tabular information that is more appropriate for the appendices at the end of this report.

Perceptual Phenomena for which the Model should account

Nearly 30 orientation perception phenomena were discussed by the experts during their efforts to summarize the perceptions already accounted for by the mathematical model of

[1] Also providing support and feedback were two non-SD specialists with extensive experience in military aviator research, physiology, and/or performance: Dr. Bruce Wright of the Civil Aeromedicine Medical Institute, and Dr. Gary Zets of Engineering Acoustics Inc.
[2] Currently affiliated with the Naval Submarine Medical Research Laboratory, Groton, CT.
[3] Currently affiliated with nuCoria (Canberra, Australia) and with Embry-Riddle Aeronautical University (Daytona Beach, FL).
[4] Currently affiliated with Wyle Science, Technology, and Engineering, Houston, TX.

orientation, the phenomena yet to be incorporated, and whether the solution to filling model gaps requires more empirical data, more refinement of the model, or both. These detailed discussions are briefly summarized in table form (Appendix 2). The consensus was that the model explains many important perceptual phenomena (Newman et al., 2012), but that more empirical laboratory data are needed from perception experiments to refine model predictions.

Key Research Gaps

Table 2 shows the type of research that is needed to improve the mathematical model of orientation perception. Key study topics are listed and prioritized in terms of their overall importance (Col A), as well as their specific importance to developing the model to maturity to allow for wider dissemination (Col B) versus extending the model to new applications not strictly essential for initial widespread dissemination (Col C).

Table 2. Key research questions.

A. Top 10 Model-Relevant Questions Needing Further Research	B. Top 5 Questions to Answer in Order to <u>Develop</u> and Mature the Model	C. Top 5 Questions to Answer in Order to <u>Extend</u> the Model to New Applications
1. How should the input from different sensory modalities be weighted to achieve an optimal estimate of the central perception of orientation and self-motion? a. Accurately predicting reliance upon visual, auditory, or tactile input during various multisensory scenarios. (Relevant to vection, 3D audio, tactile displays)	1st ranked	
2. What are the orientation/ motion perceptions and motion sickness responses to be expected during very low-frequency linear acceleration? a. Model awaits sufficient empirical data at very low frequencies, which are relevant to military vehicle effects	2nd	
3. How will orientation/motion perception estimates differ due to individual differences, e.g., in somatogravic/inversion illusions and recovery time from SD back to normal (McCarthy & Stott, 1994; Tribukait & Eiken, 2012; Kraus, 1959) a. Can the model be tailored to individuals or like subgroups of people?		1st ranked

Table 2 (Continued).

b. Can the model incorporate the time required to transition mentally from VFR to IFR during SD, or from a fully-automated vehicle to the sudden need for manual operation?		
4. What are the optimal self-motion detection thresholds to use in the model? a. Laboratory thresholds are defined, but data is lacking in the more realistic circumstanced of body motion during vehicle noise and vibration		2nd
5. What are the data inputs and model parameters for optimally estimating the Elevator Illusion? a. Need to replicate and extend Cohen (1973) with increased sample and increased G-force.	3rd	
6. What are the optimal psychophysical methods for obtaining data to improve and help to validate the model? a. Good tests are needed across different perceptual domains (Table 3)	4th	
7. How will orientation/motion perception estimates differ quantitatively due to stressors such as fatigue or workload (mental/physical)?		3rd
8. What is the best way to model a prolonged Leans illusion?		4th
9. What is needed to further validate the existing model of the Coriolis cross-coupling illusion? a. Replication and extension of Guedry and Benson (1976) and Guedry (1977) is needed w/ increased sample, a greater variety of resultant angular impulse vectors and more complete motion sickness data (Lawson, Rupert, Guedry, Grissett, & Mead 1997).	5th	
10. What is needed to refine the modeling of dynamic aspects of the G-excess illusion?		5th

Key Measures of Orientation Perception

A mathematical model of orientation perception is only as good as the empirical orientation data it models. Where perceptual data is missing in the literature or is not available in the form the model digests, extrapolations become necessary. As the model matures and is disseminated, supporting research should be carried out to fill knowledge gaps in the model (Table 2). It is important for this research to employ suitable measures of orientation and self-motion perception. Table 3 lists some current options for gathering data on orientation perception, i.e., the psychophysical measures of orientation and self-motion. The list is not comprehensive; rather, it seeks to capture the mainstream methods and a few alternate methods worth considering. Pros and cons of different methods are considered and consensus recommendations concerning the optimal application of each measure are provided. The methods are divided into several categories for convenience of discussion (e.g., verbal estimates, past-pointing, cross-modal matching, visual), but the reader should note that these categories overlap conceptually (e.g., past-pointing can be done manually or via direction of gaze).

Table 3. Measures of orientation perception.

Measure	Strengths	Limitations	Recommendations
Verbal estimation • The subject provides an estimate of his/her perceived displacement (e.g., angle or meters) or self-velocity. Two main methods are retrospective (after stimulus) or concurrent (during stimulus) reporting.	• Commonly employed in literature • Easy to set up • Fairly easy to analyze • Intuitive and rapid for subject to learn and apply • Leaves subject's eyes and hands free • Yields useful data for modeling	• Can be challenging to do concurrently with the stimulus (moment-by-moment), especially when more than one aspect of perceived orientation is being measured or if other verbal communication is required • Likely to exhibit high inter-subject variability	• An important measure that should be preserved
Past-pointing • During or immediately after the stimulus, the subject points (with hand or eyes) back to his/her original	• Task is inherently spatial in a way that is isomorphic with the stimulus (thus enhancing face validity)	• Limited application beyond the estimation of small angular displacements • Requires some additional equipment and analysis (especially for past-pointing with eyes)	• Useful clinical and laboratory measure, but not a primary source of data for an orientation model seeking to directly simulate holistic perception of

Table 3 (Continued).

heading direction prior to the start of the stimulus			body/vehicle orientation in operational environments
Cross-modal matching • Usually, a manual estimate where the subject matches a manual object (e.g., a joystick) to his/her perceived self-motion and orientation	• Commonly-employed and accepted • Yields useful data for modeling. • If desired, the subject can be trained versus an absolute standard prior to the experiment (e.g., learning where 10, 20, 30, etc. degrees are located)	• Requires some additional equipment and analysis • Requires the use of the hand • May involve use of a device typically for control inputs rather than matching of perceptions (careful instructions necessary for pilots, who must ignore their past associations with a joystick) • Subject and experimenter must understand that cross-modal and verbal estimates do not have to match each other • Difficult to use this method to measure illusion of continued velocity without further displacement (e.g., during Coriolis cross-coupling) • A frame-of-reference conundrum can emerge: if one feels that oneself, one's seat, and one's joystick apparatus are all tilted in unison, should one tilt the joystick or leave it alone? • Estimates are limited by motions possible with the hand • Many different types of cross-modal matching devices are used. Each has different pros and cons and comparison of findings from one to one another is not straightforward • Some devices may increase the likelihood of a kinesthetic memory confound concerning one's previous settings (E.g.,	• An important measure that should be preserved • Recommend expanded use of intuitive devices that simultaneously capture multiple degrees of freedom of felt self-motion (e.g., 6 DoF flying joystick; 3 DoF TPAS).

Table 3 (Continued).

		a haptic t-bar) • Devices that requires large, unconstrained arm movements during angular or linear acceleration will yield estimates affected by the acceleration	
Subjective Visual Vertical (SVV) • The subject manually adjusts a line of light in darkness (only the light is visible) until it appears to be vertically aligned with the gravity vector	• Commonly employed and accepted • Used clinically • Can be set up to avoid kinesthetic memory of prior settings (if a manual interface is used that does not provide haptic position cues)	• Requires some additional equipment and analysis • This is an indirect method: it reflects how one perceived the orientation of an external object rather than directly measuring self-orientation • Requires light in the acceleration testing chamber, which could affect nystagmus reflexes and certain aspects of orientation perception • This is a visual task so other visual tasks cannot be done while this measure is being taken • Method varies widely, rendering comparison across studies difficult	• This is a useful measure in cases where the potential drawbacks listed at left do not apply to the study contemplated. It should be considered for inclusion in any study with clinical implications • Further standardization is needed regarding whether the subject sets the line vertically or horizontally, whether the setting is done via button press (to activate a motor that adjusts the light) or other manual means (a t-bar, a joystick, a steering wheel)
Nulling Measures • The subject manually provides inputs (e.g., via a joystick) to null the perceived self-tilt or motion	• A direct behavioral measure relevant to vehicle control inputs. Should be very useful to track initial control input in response to a disorienting	• Requires significant additional equipment and analysis • Careful design and planning of measures is necessary, because if nulling inputs affect the actual orientation or motion of the subject, then the stimulus will be altered • It is more feasible to set up an apparatus where the subject	• A useful measure but one that is not often feasible • Most useful in applied part-task flight simulator studies looking at initial control inputs made in response to a disorienting

Table 3 (Continued).

	stimulus • Intuitive for pilots	attempts to null a single axis of perceived self-tilt or rotation than it is to set up an apparatus where the subject attempts to null multi-axis tilt/rotation or perceived linear translation or off-radius angular acceleration • Careful consideration and engineering limits are necessary before a subject is put in control of a large acceleration device.	acceleration stimulus • Joystick control inputs in actual flight are a very important source information for flight studies and mishap evaluations, and definitely should be included in the model
Non-Behavioral Measures • It is possible that some non-perceptual, non-behavioral measures of orientation may offer additional insight • E.g., brain activity estimates, post-cranial physiological measures	• Some non-behavioral measures do not require conscious involvement or tasking and can be assessed while the subject does other things	• Significant additional equipment and analysis is necessary • Such measures are presently indirect reflections of orientation, rather than direct measures or perceived self-tilt and motion • Disorientation in flight is usually not recognized (type I SD), therefore, any measure which seeks to reflect a conscious process may be limited • Many physiological measures are sensitive but not specific	• Such measures are useful for establishing cross-validity but are not yet primary measures of human orientation perception

Key Literature to Inform the Model

We identified the key literature findings on human spatial orientation perception for which a mature orientation model should be able to account, and categorized the key literature obtained as of historical interest (e.g., seminal works in modeling of orientation), contemporary interest (recent important modeling efforts), or interest due to the fact that they supply needed empirical data for the model (e.g., non-modeling papers with useful human orientation perceptual data in them). The list of papers is too lengthy for a table, but is shown in Appendix C.

Conclusions and Recommendations

- The model accounts for the orientation perceptions and disorienting illusions that occur during many different combinations of vestibular and visual stimuli. Further research should be conducted to foster the maturity and widespread dissemination of the orientation model for applied use.
- We identified the key research questions that need to be answered to foster model maturity. Chief among these is the need to determine how the input from different sensory modalities should be weighted to achieve an optimal estimate of the central perception of orientation and self-motion. Various studies are planned or underway (by the authors and their colleagues), which will yield data to empirically refine model weightings and thereby increase prediction accuracy.
- We identified the key research questions that need to be answered in order to extend the model with new capabilities or to apply it to new applications. Chief among these is the need to model how orientation/motion perception estimates will differ due to individual differences, such as are caused by differing levels of flying experience. In the near-term, researchers should be sure to track flight hours as a covariate in their orientation studies. In the mid-term, specific studies on this topic are needed.
- We identified the key literature findings on human spatial orientation perception for which a fully mature orientation model should eventually be able to account, and categorized the key literature as of historical interest, specific contemporary modeling interest, general interest, or interest because it supplies needed empirical data for the model. We recommend that orientation researchers use this body of research (Appendix C) as a guide when planning their research or considering existing data to exploit to make model refinements.
- We considered the available options for measurement of orientation perception, i.e., the pros and cons of different psychophysical measures that could be used to inform and validate the model. It was decided that more than one measure was generally advisable, with some important measures to consider being verbal estimation and cross-modal matching. Much research remains to be done to refine the psychophysics of human orientation. We recommend that orientation researchers plan studies with multiple, complementary measures (not necessarily assessed simultaneously in the same trial), be cautious concerning the most problematic measures on our list, and communicate among one another to agree upon a set of best measures that can be standardized or at least compared across studies. When the measurement of orientation perception is undertaken for model refinement, the key measures should be valid reflections of overall self-motion and orientation perceptions, which could reasonably be expected to influence Level I SA and decisions concerning vehicle control inputs, rather than limited assessments of one aspect of orientation function without a clear relation to the pilot's overall mental model. Of course, the key measures should be digestible by the model, i.e., quantitative

descriptions of perceived linear or angular motion that can be tested by the model. A final point is that measures should be relevant to the operational situation where one is trying to predict or reconstruct mishaps. For example, Dr. Rupert and colleagues have an effort underway to develop a cross-modal psychophysical estimate of motion and orientation that is suitable for in-flight research and demonstration.

- To date, the mathematical model of orientation has been used to simulate perceptual findings from laboratory motion experiments or to assist with post-hoc aeromedical evaluation of potential perceptual factors contributing to known aviation mishaps (Rupert, Woo, Brill, & Lawson, 2016; Rupert & Lawson, 2015; Newman et al., 2012; Newman et al., 2016). A potential long-term goal for model development would be to produce an in-cockpit early warning system that could predict disorientation prior to loss of situation awareness and thereby prevent SD mishaps (Lawson et al., 2015; Thompson et al., 2016).

References

Benson, A. J. (1989). Spatial disorientation—general aspects. In: Ernsting J., ed. *Aviation Medicine*. London: Butterworths.

Boeing. (2014). Fatalities by CICTT Aviation Occurrence Categories. 2013 Statistical Summary, August 2014. Retrieved from http://www.boeing.com/news/techissues/pdf/statsum.pdf.

Braithwaite, M. G., DeRoche, S. L., Alvarez, E. A., & Reese, M. A. (1997). *Proceedings of the First Triservice Conference on Rotary-Wing Spatial Disorientation: Spatial Disorientation in the Operational Rotary-Wing Environment*. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL.

Braithwaite, M. G., Durnford, S. J., Crowley, J. S., Rosado, N. R., & Albano, J. P. (1998). Spatial disorientation in US Army rotary-wing operations. *Aviation, Space, and Environmental Medicine, 69*(11), 1031-1037.

Cohen, M. M. (1973). Elevator Illusion – Influences of otolith Organ Activity and Neck Proprioception. *Perception and Psychophysics, 14*, 401-406.

Collins, W., & Dollar, C. (1996). *Fatal General Aviation Accidents Involving Spatial Disorientation*: 1976-1992 (Final Report).

Endsley, M. R. (1995) A taxonomy of situation awareness errors. Human Factors in Aviation Operations, Vol. 3, 287-298. As cited in Jones, D.G., & Endsley M.R. (1996). Sources of situation awareness errors in aviation. *Aviation, Space and Environmental Medicine, 67*(6), 507-512.

Edens, T. J., & Higginbotham, M. D. (2014). Degraded visual environments: a leading factor in aviation accidents. *Army Aviation Magazine*, 31 March, 22-23.

Gibb, R.W., Ercoline, B., & Scharff, L. (2011). Spatial disorientation: decades of pilot fatalities. *Aviation, Space, and Environmental Medicine*, *82*(7), 717-724.

Gibb, R.W., Gray, R., & Scharff, L. (2010). *Aviation Visual Perception: research, misperception, & mishaps*. Surrey, England: Ashgate Publishing Ltd.

Guedry, F. E., & Benson, A. J. (1976) Coriolis cross-coupling effects: Disorienting and nauseogenic or not? *Aviation, Space and Environmental Medicine*, *49*(1), 29-35.

Guedry, F. E. (1977). *Visual Counteraction of Nauseogenic and Disorienting Effects of Some Whole-Body Motions--A Proposed Mechanism* (No. NAMRL-1232). Naval Aerospace Medical Research Laboratory, Pensacola, FL.

Kirkham, W. R., Collins, W. E., Grape, P. M., Simpson, J. M., & Wallace, T. F. (1978). Spatial disorientation in general aviation accidents. *Aviation, Space, and Environmental Medicine*, *49,* 1080-1086.

Kraus, R. N. (1959). Disorientation in flight, an evaluation of the etiological factors. *Aerospace Medicine*, 30:664-673.

Lawson, B. D., Rupert, A. H., Guedry, F. E., Grissett, J. D., & Mead, A. M. (1997). The human-machine interface challenges of using virtual environment (VE) displays aboard centrifuge devices. *Advances in human factors/ergonomics*, 945-948.

Lawson, B. D., Smith, S. A., Kass, S. J., Kennedy, R. S., & Muth, E. R. (2003). *Vestibular stimuli may degrade situation awareness even when spatial disorientation is not experienced*. Proceedings of the RTO HFM Symposium on Spatial Disorientation in Military Vehicles, RTO-MP-086, 43-1 to 43-21.

Lawson, B. D., McGrath, B. J., Newman, M. C., & Rupert, A. H. (2015). *Requirements for developing the model of spatial orientation into an applied cockpit warning system.* Proceedings of the 18th International Symposium on Aviation Psychology, Dayton, OH, 4-7 May

McCarthy G. W., & Stott J. R. (1994) In flight verification of the inversion illusion. *Aviation, Space, and Environmental Medicine*, *65*(4), 341-344.

Mortimer, R. G. (1995). *General aviation airplane accidents involving spatial disorientation*. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 39, No. 1, pp. 25-29). SAGE Publications.

Newman, M. C., Lawson, B. D., Rupert, A. H., & McGrath, B. J. (2012). *The role of perceptual modeling in the understanding of spatial disorientation during flight and ground-based simulator training.* Proceedings of the American Institute of Aeronautics and Astronautics, 15 Aug., Minneapolis, MN, 14 pages.

Newman, M. C., Lawson, B. D., Rupert, A. H., McGrath, B. J., Hayes, A. M., & Milam, L. S. (2016). *A Model of Human Orientation and Self-Motion Perception during Body Acceleration: The Orientation Modeling System*. (Report No. 2016-22) USAARL.

Newman, M. N., Lawson, B. D., McGrath, B. J., & Rupert, A. H. (2014). *Perceptual modeling as a tool to prevent aircraft upset associated with spatial disorientation*. Proceedings of the American Institute of Aeronautics and Astronautics, 14 Jan., National Harbor, MD, 11 pages.

Poisson, R. J., & Miller, M. E. (2014). Spatial disorientation mishap trends in the U.S. Air Force 1993-2013. *Aviation, Space, and Environmental Medicine, 85*(9), 919-924.

Rupert, A. H., & Lawson, B. D. (2015) *Tatarstan Airlines Flight 363 Mishap: Perceptual Study*. (Tech Memo 2015-03), 12 pages USAARL. (Distribution limited.)

Rupert, A. H., Woo, G., Brill, J., & Lawson, B. (2016). *Countermeasures for loss of situation awareness: Spatial orientation modeling to reduce mishaps*. In Aerospace Conference, March IEEE (pp. 1-9). IEEE.

Singh, B., & Navathe, P. D. (1994). Indian Air Force and world spatial disorientation accidents: a comparison. *Aviation, Space, and Environmental Medicine*, *65*, 254-256.

Tormes, F. R., & Guedry, F. E. (1975). Disorientation phenomena in naval helicopter pilots. *Aviation, Space, and Environmental Medicine*, *46*, 387-393.

Thompson, L. I., Lawson B. D., Newman, M. C., McGrath, B. J., Brill, J. C., & Rupert, A. H. (2016). *Design considerations and research needs for expanding the current perceptual model of spatial orientation into an in-cockpit spatial disorientation warning system* (Report No. 2017-07). Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory.

Tribukait, A., & Eiken, O., (2012) Flight experience and the perception of pitch angular displacements in a gondola centrifuge. *Aviation, Space, and Environmental Medicine*, *83*(5), 496-503.

Veronneau, S. J., & Evans, R. H. (2004). Spatial disorientation mishap classification, data, and investigation. *Spatial Disorientation in Aviation*, (Eds.), Previc, F.H. and Ercoline, W.R., Progress in Aeronautics and Astronautics, 203, 197-241.

Appendix A. Spatial Orientation Modeling Expert Workgroup (SOMEW) Meeting Agenda

16-17 June, 2015

Hosts: Angus Rupert and Ben Lawson.

Site: U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL.

Sponsor: Small Business Innovative Research program.

Purpose.

To generate specific consensus recommendations concerning gaps in the current mathematical model of orientation, needed research to refine the model, perceptual measures for validating the model, and gaps in current countermeasures for spatial disorientation.

Agenda.

Tuesday 08:00 16 June

08:00 Auditory Protection and Performance conference room sign-in, coffee

08:10 Introductions, scope of SBIR and DHP JPC AMP Modeling projects

08:30 Current state of the art –

Mishap analysis examples

Inadequacies of current models and future research needed

10:00 Break

10:10 Limitations to current SD countermeasures and recommendations concerning model extensions (E.g., 3D Audio, tactile)

12:00 Onsite lunch (estimated cost $10.99/person)

13:00 – 1400 demonstrations

14:00 Recommendation of measures of perceived orientation for model validation

16:45 Adjourn for the day

18:00 Interested participants meet for dinner

Wednesday 08:30 17 June

08:00 Consideration of interactions and synergies of illusions

09:00 Recommendation of graphical user interfaces for modeling

10:00 Recommendation for model expansion beyond mishap simulation

Ground-based model (e.g., for simulation)

In-flight warning[5]

11:00 Drafting of summary consensus recommendations and action items

12:00 Meeting adjourned. Interested participants lunch together before traveling home

[5] This topic is discussed in Thompson et al., USAARL Report No 2016-07.

Appendix B. Summary of Expert Discussion Points Concerning Model Capabilities and Needs

This Appendix briefly summarizes nearly 30 points discussed by the experts during their efforts to summarize the perceptual phenomena already accounted for by the mathematical model of orientation, the phenomena yet to be incorporated, and whether the solution to filling model gaps requires more empirical data, more refinement of the model, or both. The papers of the authors mentioned below can be found in the Reference section of this report or in Appendix C.

Capabilities: Phenomena Currently Modeled		**Needs: Phenomena to be Incorporated**	**Solutions: Requirements to Fill Needs**
1.	Perception of real whole-body rotation (per and afteroration) in darkness and as modified by cues from visual surround	Perception of real whole-body rotation (per and afteroration) in darkness as modified by auditory or somatosensory cues (Bles, Van Der Heijde, Kotaka, & Reulen, 1985) • Helpful Earth-referenced auditory or somatosensory cues • Disruptive effects of loud noise and vehicle vibration (to identify self-motion detection thresholds in applied settings)	More data to inform the model
2.	Perception of apparent whole-body rotation (circular-vection and optokinetic after-rotation)	More refined estimates of time-to-onset of circular-vection and influence of focal and peripheral cues on vection intensity.	More data to inform the model and better prediction of existing data
3.	Perception of apparent whole-body translation (linear-vection)	More refined estimates of time-to-onset of linear-vection and influence of focal and peripheral cues on vection intensity.	More data to inform the model and better prediction of existing data
4.	Perception of self-orientation/motion during head movement while rotating (Coriolis cross-coupling)	Needs: • Refined laboratory estimates of time course of the illusion. • Refined laboratory estimates of the velocity versus displacement aspect of the illusion. o Some info in Dizio and in Holly and Harmon (2009) and Holly, Vrublevskis, and Carlson, (2008) papers. • Modification of Coriolis cross-	More data to inform the model and better prediction of existing data

		coupling by somatosensory cues.	
5.	Perception of self-orientation/motion during head movement immediately after rotating (dumping)	Modification of dumping by somatosensory cues	More data to inform the model
6.	Perception of self-orientation during increased G-force (somatogravic illusion)	Would be nice if model also accounted for different types of inversion illusions also (a variant of somatogravic), including tilting versus telescoping through one's body vs. sudden switching (Lackner, 1992).	More data to inform the model
7.	Perception of self-orientation during head movement under altered G-force (G-excess illusion)	• G-excess under identical G-levels produced by different radii of centrifugation or aircraft banking turns. • E.g., replication of Gilson et al. study on larger sample and with more stimuli (1973)	More data to inform the model
8.	Model is good with individual sensory modalities	Model needs more multisensory capability	More data to inform the model and better prediction of existing data
9.	Model is good at estimating eye movements	Eye movements don't always match perception; model needs to improve concerning functional implications of nystagmus for estimates of dynamic visual acuity (at what points in time can you not read instruments due to nystagmus?)	More data to inform the model and better prediction of existing data
10.	Model now estimates perception when you do or do not have sight of instruments or outside world.	Model does not distinguish site of instruments versus outside world (assumes same effect on orientation; however, most instruments are not an isomorphic representation of the natural world and require abstract thought which will cause a delay in decision-making). Also, we currently don't have direction of gaze information being gathered routinely and fed into the model. Need: effects of gaze direction on model.	More data to inform the model
11.	Model works under	Even if model was receiving gaze	More data to

	assumption of normal cognitive state	information, model currently does not account for instances when one is "looking but not seeing," i.e., looking at the world or instruments, but not cognitively interpreting them, due to distraction (e.g., habitually following instrument scan pattern without attending to each new bit of information properly due to intruding thoughts), cognitive blindness (e.g., looking for a car and not seeing one, then pulling out in front of a motorcyclist), staring into space (e.g., during fatigue or daydreaming), eyelid closure (not seeing during blinking or eyelid drooping), saccadic suppression (not seeing during small eye movements), non-foveation (looking towards but not directly at a target). • Short-term Need: o Quantify (and incorporate into model) the duration of gaze at primary instruments prior to making correct input (under normal versus disoriented conditions) • Longer-term Needs: o Estimate of effect of fatigue on model. o Needs: Estimate of effect of stress/anxiety/workload on model	inform the model
12.	Model can adjust for different planetary G-levels	Model should be able to adjust for different periods of exposure/adaptation to a particular G	More data to inform the model
13.	Model predicts perceptual data from many published studies	• Comprehensive list of all important studies is needed, to determine what important phenomena from the literature are not yet incorporated into the model • Many publications don't contain enough raw data to inform the model, so one has to contact the authors	More data to inform the model

14.	Model estimates many perceptions when proper acceleration data files are prepared and uploaded.	• Model input files are often labor intensive to create. A user-friendly interface is in preparation that transforms motion device or aircraft data (e.g., transforming acceleration vectors for the user) to model input. This will help investigators use the model more easily and rapidly. • Many legacy military aircraft still lack a "black box" flight data recorder to allow more accurate estimates of moment-by-moment acceleration. This is needed, b/c currently this info must be inferred, (e.g., from radar hits) whereas it is known with high fidelity during commercial flight. • Black box data is also often under sampled and methods need to be developed to transform these sparse data sets to higher sample rates (e.g. 100Hz). • Black box data is often not recorded at the center of the pilot's head. Transformation from aircraft center of gravity to pilot coordinates needs to be considered before accident analysis or modeling.	Better user interfacing with existing data; better aircraft data to feed in as input files to the model. A user-friendly interface that transforms motion device or aircraft data to model input would help investigators rapidly generate input files. Perhaps modeling approach of Holly, Vrublevskis, and Carlson could be used at the input stage of the model to transform the physics of vehicle accelerations into terms the model can digest (2008)[6].
15.	Vestibular parameters of model are getting fairly mature	• Visual and visual-vestibular parameters need more refinement. • Somatosensory and auditory parameters are lacking. • Army requires 3D audio and tactile cueing solutions for in-flight displays. These refinements are underway.	More data to inform the model and better prediction of existing data

[6] Examples of Holly's approach in multiple cases is given by her lecture in Lawson et al., 2014 (Appendix C)

16.	Model does a good job estimating average, normal response	Model could expand to allow for some of the individual variability in orientation perception that has been confirmed by the literature, e.g. by having baseline or in-flight data on: • Role of flight experience in perception of motion (McCarthy & Stott, 1994). Possibly different perceptions and different susceptibility to SD (but had limited sample and needs replication and extension). • Clinical aspects of response (vestibular pathology) as they affect orientation perception. o A growing military and VA need and an important civilian need which dwarfs spatial disorientation aircraft mishaps. • Individual variability in time course of perceived angular tilt (Tribukait & Eiken, 2012). • Sex effects on orientation perception, e.g., field dependency, field of view, etc. Limited research here.	More data to inform the model and better prediction of existing data
17.	Model predicts orientation perception	Model needs to be refined to predict likelihood of disorientation and also type of disorientation (type I, II, or III).	More data to inform the model and better prediction of existing data
18.	Model predicts orientation perception and some types of disorientation and motion sickness (Oman, 1982).	Model is being refined further to improve the prediction of motion sickness • Better quantitative estimates of real and apparent motion stimuli causing sickness • Better understanding and prediction of effects of stimuli that cause both disorientation and sickness • Better understanding of interactions between disorientation and sickness	More data to inform the model and better prediction of existing data

19.	Model predicts a range of linear motion frequencies	• More data is needed on very low-frequencies of linear oscillation, to inform both orientation model and the motion sickness model (for human factors design as in mil stds). o E.g., well-known McCauley curve has incomplete data at low frequencies, where it is more conjectural. Need to expand the curve and validate it empirically. • Some of this type of work feeds directly back into understanding otolith processing better, which is less understood than canal function.	More data to inform the model
20.	Model does fairly well now at predicting Coriolis cross-coupling or somatogravic	Need further development to understand interaction between cross-coupling and somatogravic, as well as those phenomena versus G-excess. What is the ultimate perception when multiple illusions are happening?	More data to inform the model and better prediction of existing data
21.	Model generally assumes passive passenger (unless comparing stick inputs to perceptions)	Model needs to incorporate expectation, motor commands, and reafference. • E.g., to know if the pilot is disoriented, it would help if the model had some idea of the pilot's flight instructions, intentions, or what he/she wanted to do at that moment. • E.g., different perceptions when self-turning is actively generated. • E.g., experiments where subject is in the control loop of the vehicle, providing inputs • Different motion sickness response occurs with or without reafference, but it is not as clear how the perception will be altered in many cases based on the presence or absence of reafference.	More data to inform the model and better prediction of existing data
22.	Presently, there are three	Meta-gap:	More data to

	main types of orientation modeling: orientation perception; eye movement, and motion sickness. With certain exceptions Oman (1982) and Bos and Bles, (2002), these are usually separate lines of modeling with limited overlap.	• Desirable to coordinate across modeling silos so that one meta-model accounts for perception, reflexive gaze, and motion malaptation responses to be expected with a given stimulus. • Moreover, model does not account for how motion sickness affects your subsequent behavior (e.g., head and eye movements) and resulting perceptions.	inform the model and better prediction of existing data
23.	Model predicts initial perception similar to transient leans	• Model needs to be better at accounting for prolonged leans. • Research needed to refine knowledge of exactly when leans is triggered, how long it lasts with different stimuli, and how much lean angle should be expected with different stimuli.	More data to inform the model and better prediction of existing data
24.	Model incorporates presence/absence of vision	• Model does not fully account for focal versus ambient visual functions. • Perhaps a non-deterministic model or partial visual state modeling instead of vision off/on. • Could weight strength of visual cues re. maintaining orientation as a start. o But how to account for fact that partial, impoverished vision may help you OR may be unhelpful AND prevent you from relying solely upon your instruments.	More data to inform the model and better prediction of existing data
25.	Model predicts many vestibular and visual-vestibular sensations.	Model lacks kinesthesia. Need data to use to weight a kinesthetic aspect of the model appropriately. (Borah?)	More data to inform the model
26.	Model predicts average perceptions	Model does not have a formal false positive and false negative capability estimate for predictions. (this came up in the context of a model-based cockpit display, so perhaps not critical at this juncture).	Better prediction of existing data

Appendix C. Relevant Papers

A list of relevant orientation perception papers is provided in this Appendix. These are the main papers which inform (or could inform) the current mathematical model as of the time of the meetings reported in this paper.

Key to the Papers

The list of papers below falls into four conceptual categories. For the convenience of the reader, these four categories are distinguished cosmetically via different font types:

1. **Modeling Papers**: Citations in **bold font** specifically discuss the mathematical modeling of human spatial orientation perception.
2. <u>Data Papers</u>: Citations which are in <u>underlined font</u> below are included primarily because they contain usable data of potential importance to the model.
3. *Historically Important Papers:* Citations in *italics font* are of historic interest to the development of orientation models.
4. General Interest Papers: Citations in regular font are of general interest, e.g., because they raise important conceptual or operational points of which modelers should be aware.

These four categories are simplifications, since many papers could appear in more than one category, e.g., many modeling papers also contain useful modeling data, some historical papers contain elements of modeling which are still used today, and some papers of general interest are also modeling papers in a different domain of human functioning from human holistic perception of self-orientation and motion.

1. Adelstein, B. D., Beutter, B. R., Kaiser, M. K., McCann, R. S., Stone, L. S., Anderson, M. R., & Paloski, W. H. (2009). Influence of combined whole-body vibration plus G-loading on visual performance. Moffett Field, CA: NASA Ames Research Center.
2. Andrade, E. B. (2011). Excessive confidence in visually-based estimates. Organizational Behavior and Human Decision Processes, 116(2), 252-261.
3. Benson, A. J. (1999a). Spatial disorientation - general aspects. In J. Ernsting, A.N. Nicholson, D. J. Rainford (Eds.), Aviation Medicine, (3rd ed., pp.419-436), Oxford: Butterworth Heinemann.
4. Benson, A. J. (1999b). Spatial disorientation - common illusions. In J Ernsting, AN Nicholson, D. J. Rainford (Eds.), Aviation medicine, (3ed., pp.437-481), Oxford: Butterworth Heinemann.
5. **Bortolami, S. B., Rocca, S., Daros, S., DiZio, P., & Lackner, J. R. (2006). Mechanisms of human static spatial orientation. Experimental brain research, 173(3), 374-388.**
6. Bertolini, G., Ramat, S., Laurens, J., Bockisch, C. J., Marti, S., Straumann, D., & Palla, A. (2011). Velocity storage contribution to vestibular self-motion perception in healthy human subjects. Journal of neurophysiology, 105(1), 209-223.

7. **Bilien, V. (1993) Modeling human spatial orientation perception in a centrifuge using estimation theory. S.M. Thesis, Man-Vehicle Laboratory, Cambridge, Massachusetts: Massachusetts Institute of Technology.**
8. Bles, W., Van Der Heijde, G. L., Kotaka, S., & Reulen, J. P. H. (1985). Some modelling aspects of nystagmus due to somatosensory-visual-vestibular interactions in stepping around. In Vestibular and visual control on posture and locomotor equilibrium (pp. 38-42). Karger Publishers.
9. **Borah, J., Young, L. R., & Curry, R. E., (1988). "Optimal Estimator Model for Human Spatial Orientation. Representation of Three-Dimensional Space in the Vestibular, Oculomotor, and Visual System," Annals of the New York Academy of Sciences, Vol. 545, pp. 51-73.**
10. **Borah, J., Young, L. R., & Curry, R. E. (1978). Sensory mechanism modeling. Air Force Human Resources Laboratory, Air Force Systems Command, AFHRL-TR-78-83.**
11. Bortolami, S. B., Rocca, S., Daros, S., DiZio, P., & Lackner, J. R. (2006). Mechanisms of human static spatial orientation. Experimental Brain Research, 173(3), 374-388.
12. **Bos, J. E., & Bles, W. (2002). Theoretical considerations on canal–otolith interaction and an observer model. Biological cybernetics, 86(3), 191-207.**
13. Braithwaite, M. G. (1997). The British Army Air Corps in-flight spatial disorientation demonstration sortie. Aviat Space Environ Med. Apr;68(4):342-5.
14. Braithwaite, M., Groh, S., & Alvarez, E. (1997). Spatial Disorientation in U.S. Army Helicopter Accidents: An Update of the 1987-92 Survey to Include 1993-1995. USAARL Report No. 97-13.
15. Brown D.L., Vitense H. S., Wetzel P. A., & Anderson G. M. (2002). Instrument scan strategies of F-117A pilots. Aviat Space Environ Med. Oct;73(10):1007-13.
16. Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA) (2013). Study on Aeroplane State Awareness during Go-around. Published August 2013.
17. Caiger B. (1972). Relation between a pilot's sensory perception of linear accelerations and the aircraft motion. Aviat Space Environ Med. Sep;43(9):957-8.
18. Chelette, T. L., Martin, E. J. & Albery, W. B., (1995). The effect of head tilt on perception of self-orientation while in a greater than one G environment. Journal of Vestibular Research: Equilibrium & Orientation.
19. Cheung B., & Bateman W. A. (2001). G-transition effects and their implications. Aviat Space Environ Med. Aug;72(8):758-62.
20. **Clark, T. K., Newman, M. C., Oman, C. M., Merfeld, D. M., & Young, L. R. (2015). Modeling human perception of orientation in altered gravity. Frontiers in systems neuroscience, 9.**
21. Clark, T. K., Newman, M. C., Oman, C. M., Merfeld, D. M., & Young, L. R. (2015). Human perceptual overestimation of whole body roll tilt in hypergravity. Journal of Neurophysiology, 113(7), 2062-2077.
22. Clark, T. K. (2013). Human Perception and Control of Vehicle Roll Tilt in Hyper-Gravity. Ph.D. Thesis, Man-Vehicle Laboratory, Cambridge, Massachusetts: Massachusetts Institute of Technology.
23. Clark, T. K., Young, L. R., Duda, K. R, & Oman C. M. (2012). Simulation of Astronaut Perception of Vehicle Orientation during Planetary Landing Trajectories. IEEE Aerospace Conference, Big Sky, MT.

24. Clark, T. K., Young, L. R., Stimpson, A. J., Duda, K. R., & Oman C. M. (2011). Numerical Simulation of Human Orientation Perception during Lunar Landing. Acta Astronautica 69:420-428.
25. Cohen M. M., Crosbie R. J., & Blackburn L. H. (1973). Disorienting effects of aircraft catapult launchings. Aerosp Med. Jan;44(1):37-9.
26. Cohen, M. M. (1973). Elevator Illusion – Influences of otolith Organ Activity and Neck Proprioception. Perception and Psychophysics 14:401-406.
27. Correia Grácio, B. C., De Winkel, K. N., Groen, E. L., Wentink, M., & Bos, J. E. (2013). The time constant of the somatogravic illusion. Experimental Brain Research, 224(3), 313-321.
28. Correia, M. J., Luke, B. L., McGrath, B. J., Clark, J. B., & Rupert, A. H. (1996). The role of linear acceleration in visual-vestibular interactions. Journal of Vestibular Research, 4(6), S51.
29. Correia, M. J., Hixson W. C. & Niven J. I. (1968). On Predictive Equations for Subjective Judgments of Vertical and Horizon in a Force Field. Acta Otolaryngologica (supplement) 230:1-20.
30. Corvera, J. Hallpike, C. S., & Schuster E. H. J. (1958). A New Method for the Anatomical Reconstruction of the Human Macular Planes. Acta Otolaryngolgica 49:4-16.
31. Crognale, M. A., & Krebs, W. K. (2011). Performance of helicopter pilots during inadvertent flight into instrument meteorological conditions. The International Journal of Aviation Psychology, 21(3), 235-253.
32. Curthoys, I. S., Betts G. A., Burgess A. M., MacDougall H. G. Cartwright A. D., & Halmagyi G. M. (1999). The Planes of the Utricular and Saccular Maculae of the Guinea Pig. Annals of the New York Academy of Sciences 871:27-34.
33. Drakunov, & Drakunov, S. V. (1992). "Sliding-mode observers based on equivalent control method" Proceedings of the 31st IEEE Conference on Decision and Control: 2368-2369.
34. Drakunov, S. V., & Utkin V.I. (1995). "Sliding mode observers. Tutorial." Proceedings of the 34 IEEE Conference on Decision and Control, V. 4, 3376 - 3378.
35. Dyde, R.T., Jenkin, M.R., Jenkin, H.L., Zacher, J.E. & Harris, L.R. (2009). The effect of altered gravity states on the perception of orientation. Experimental brain research, 194(4), pp.647-660.
36. Ellis, S. R., & Stark, L. (1986). Statistical Dependency in Visual Scanning. Human Factors. 28(4), 421-438.
37. Ercoline W. R., Devilbiss C. A., Yauch D. W., & Brown D. L. (2000) Post-roll effects on attitude perception: "the Gillingham Illusion". Aviat Space Environ Med. May; 71(5):489-95.
38. *Fernandez C., & Goldberg, J. M. (1976a). Physiology of peripheral neurons innervating otolith organs of the squirrel monkey. I. Response to static tilts and to long-duration centrifugal force. Journal of Neurophysiology, 39(5):970–984.*
39. *Fernandez C., & Goldberg, J. M. (1976b). Physiology of peripheral neurons innervating otolith organs of the squirrel monkey. II. Directional selectivity and force-response relations. Journal of Neurophysiology, 39(5):985–995.*
40. *Fernandez C., & Goldberg, J. M. (1976c). Physiology of peripheral neurons innervating otolith organs of the squirrel monkey. III. Response dynamics. Journal of Neurophysiology, 39(5):996–1008.*
41. Gibb, R., Ercoline, B., & Scharff, L. (2011). Spatial disorientation: decades of pilot fatalities. Aviation, Space, and Environmental Medicine, 82(7), 717-724.

42. Gillingham, K. K. & Previc, F. H. (1996). Spatial orientation in flight. In: R. L. DEHART (Ed), Fundamentals of Aerospace Medicine. Williams and Wilkins, Baltimore, MD, 309-97.
43. Gillingham, K. K. & Wolfe, J. W. (1986). Spatial orientation in flight. In: R. L. DEHART (Ed), Fundamentals of Aerospace Medicine. Lea and Febiger, Philadelphia, PA, 299-381.
44. Gilson R. D., Guedry F. E. Jr, Hixson W. C., & Niven J. I. (1973) Observations on perceived changes in aircraft attitude attending head movements made in a 2-g bank and turn. Aerosp Med. Jan;44(1):90-1
45. Goldberg, J., & Fernandez, C. (1971a). Physiology of peripheral neurons innervating the semicircular canals of the squirrel monkey. I. Resting discharge and response to constant angular accelerations. Journal of Neurophysiology, 34(4):635-660.
46. Goldberg, J., & Fernandez, C. (1971b). Physiology of peripheral neurons innervating semicircular canals of the squirrel monkey. II. Response to sinusoidal stimulations and dynamics of peripheral vestibular system. Journal of Neurophysiology, 34(4):661-675.
47. *Graybiel A., Johnson W. H., Money K. E., Malcolm R. E., & Jennings G. L.(1979) Oculogravic illusion in response to straight-ahead acceleration of CF-104 aircraft. Aviat Space Environ Med. Apr; 50(4):382-6.*
48. **Grissett, J. D. (1993) “Mathematical Model for Interaction of Canals and Otoliths in Perception of Orientation, Translation, and Rotation,” NAMRL Special Report 93-5, Naval Aerospace Medical Research Laboratory, Pensacola, FL.**
49. Guedry F. E., & Rupert A. H. (1991) Steady state and transient G-excess effects. Aviat Space Environ Med. Mar;62(3):252-3.
50. Guedry F. E. (1992). Perception of motion and position relative to the earth. An overview. Ann N Y Acad Sci. 1992 May 22; 656:315-28.
51. *Guedry, F. E. (1977). Visual Counteraction of Nauseogenic and Disorienting Effects of Some Whole-Body Motions--A Proposed Mechanism (No. NAMRL-1232). Naval Aerospace Medical Research Lab Pensacola, Fl.*
52. *Guedry, F. E., & Benson, A. J. (1976). Coriolis cross-coupling effects: Disorienting and nauseogenic or not? Aviation, Space and Environmental Medicine, 49(1):29-35.*
53. Gueguen, M., Vuillerme, N., & Isableu, B. (2012). Does the integration of haptic and visual cues reduce the effect of a biased visual reference frame on the subjective head orientation? PloS one, 7(4), e34380.
54. **Haslwanter, T., Jaeger, R., Mayr, S., & Fetter, M. (2000). Three-dimensional eye-movement responses to off-vertical axis rotations in humans. Experimental Brain Research, 134(1):96-106.**
55. Hess, Bernhard J. M., & Angelaki, D. E. (1997). Inertial vestibular coding of motion: concepts and evidence. Current Opinion in Neurobiology 7.6: 860-866.
56. *Hixon, W. C., Niven, J. I., & Correia, M. J. (1966). Kinematices nomenclature for physiological accelerations. Monograph 14, Naval Aerospace Medical Institute, Naval Aerospace Medical Center, Pensacola, FL.*
57. **Holly, J. E., & Harmon, K. J. (2009). Spatial disorientation in gondola centrifuges predicted by the form of motion as a whole in 3-D. Aviation, space, and environmental medicine, 80(2), 125.**
58. Holly, J. E., Vrublevskis, A., & Carlson, L. E. (2008). Whole-motion model of perception during forward-and backward-facing centrifuge runs. *Journal of Vestibular Research, 18*(4), 171-186.

59. *Holst, E. V., & Mittelstaedt, H. (1971). The principle of reafference: Interactions between the central nervous system and the peripheral organs. PC Dodwell (Ed. and Trans.), Perceptual processing: Stimulusequivalence and pattern recognition, 41-71.*
60. Isu, N., Yanagihara, M. A., Yoneda, S., Hattori, K., & Koo, J. (1996). The severity of nauseogenic effect of cross-coupled rotation is proportional to gyroscopic angular acceleration. Aviation, space, and environmental medicine, 67(4), 325-332.
61. Jaslow H. (1980). Equiperception maneuvers. Aviat Space Environ Med. Sep;51(9 Pt 1):867-71.
62. Jia, H., Yu, L., Bi, H., Wang, K., Liu, Z. & Xie, S. (2002). Perception of the cabin attitude changes in hypergravity. Aviation, space, and environmental medicine, 73(3), pp.191-193.
63. Johnson, J. C., & Priser, D. B. (1981). Vibration Levels in Army Helicopters--Measurement Recommendations and Data (No. USAARL-81-5). U.S. Army Aeromedical Research Laboratory; Fort Rucker, AL.
64. **Karmali, F., & Merfeld, D. M. (2012). A distributed, dynamic, parallel computational model: the role of noise in velocity storage. Journal of Neurophysiology 108:390-405.**
65. Kraus, R. N. (1959). Disorientation in flight, an evaluation of the etiological factors. Aerospace Medicine. 30:664-673.
66. **Kynor, D. B. (2002). Disorientation Analysis and Prediction System (DAPS). Final Report AFRL-HE-WP-TR-2002-0179, United States Air Force Research Laboratory, Wright-Patterson Air Force Base, OH.**
67. **Kynor, D. B., Dietz, A. J., Berg, J. I., Hill, R. W., Audette, W. E., & Kaszeta, R. W. (2004). Disorientation Analysis and Prediction System. Final Report (AFRLIHE-WP-TR-2004-0159), United States Air Force Research Laboratory, Wright-Patterson Air Force Base, OH.**
68. Lackner, J. R. (1992). Spatial orientation in weightless environments. *Perception*, *21*(6), 803-812.
69. **Lackner, J. R., & DiZio, P. (2008). *Models and Mechanisms for Enhanced Sensory-Motor Control*. BRANDEIS UNIV WALTHAM MA ASHTON GRAYBIEL SPATIAL ORIENTATION LAB.**
70. **Laurens J., & Droulez J. (2007). Bayesian processing of vestibular information. Biological Cybernetics, 96(4):389-404.**
71. Lawson, B. D., Guedry, F. E., Rupert, A. R., & Anderson, A. M. (1993). Attenuating the disorienting effects of head movement during whole-body rotation using a visual reference: Further tests of a predictive hypothesis. Proceedings, "Virtual Interfaces: Research and Applications" October, NATO AGARD,
72. Lawson, B. D., Rupert, A. H., Guedry, F. E., Grissett, J. D., & Mead, A. M. (1997). The human-machine interface challenges of using virtual environment (VE) displays aboard centrifuge devices. Advances in Human Factors/Ergonomics, 945-948.
73. Lawson, B. D., Rupert, A. H., Raj, A. K., Parker, J. N., & Greskovich, C. (2014). Invited Lectures from a Spatial Orientation Symposium in Honor of Frederick Guedry, Day 1 (No. USAARL-2014-10). U.S. Army Aeromedical Research Laboratory; Fort Rucker, AL.
74. Lawson, B. D., Smith, S. A., Kass, S. J., Kennedy, R. S., & Muth, E. R. (2002). Vestibular stimuli may degrade situation awareness even when spatial disorientation is not experienced. RSK ASSESSMENTS INC ORLANDO FL.
75. **Lawson, B. D., McGrath, B. J., Newman, M. C., & Rupert, A. H. (2015). Requirements for developing the model of spatial orientation into an applied cockpit warning system.**

Proceedings of the 18th International Symposium on Aviation Psychology, Dayton, OH, 4-7 May.

76. Lee, Y. C., Lee, J. D., & Boyle, L. N. (2007). Visual attention in driving: the effects of cognitive load and visual disruption. Human Factors: The Journal of the Human Factors and Ergonomics Society, 49(4), 721-733.
77. Lentz J. M., & Guedry F. E. Jr. (1982) Apparent instrument horizon deflection during and immediately following rolling maneuvers. Aviat Space Environ Med. Jun; 53(6):549-53.
78. Lessard, C. S., Matthew, R. & Yauch, D. (2000). Effects of rotation on somatogravic illusions. Engineering in Medicine and Biology Magazine, IEEE, 19(2), pp.59-65.
79. *Luenberger, D. G. (1971). An introduction to observers. IEEE Transactions on Automatic Control 16(6):596-602.*
80. Lyons T. J., Simpson C. G. (1989) The giant hand phenomenon. Aviat Space Environ Med. Jan; 60(1):64-6.
81. Malcolm R., & Jones, G. M. (1974) Erroneous perception of vertical motion by humans seated in the upright position. Acta Otolaryngol. Apr; 77(4):274-83.
82. Masica, R. M. (2009). A study to evaluate the suitability of a centrifuge as a dynamic flight simulator for F/A-18 strike fighter mission training. Masters Theses, 543.
83. Mayne, R. (1974) A systems concept of the vestibular organs. In: Kornhuber H (ed) Handbook of Sensory Physiology, vol VI. vestibular system, part 2: psychophysics, applied aspects and general interpretations. Springer, Berlin Heidelberg NY, pp 493–580
84. McCarthy G. W., & Stott J. R. (1994) In flight verification of the inversion illusion. Aviat Space Environ Med. Apr; 65(4):341-4.
85. McGrath, B. J., Rupert, A. H., & Guedry, F. E. (2003). Analysis of spatial disorientation mishaps in the US Navy. Naval Aerospace Medical Research Laboratory, Pensacola, FL.
86. McGrath, B. J., Estrada, A., Braithwaite, M. G., Raj, A. K., and Rupert, A. H. (2004). Tactile Situation Awareness System Flight Demonstration Final Report. USAARL Tech Report No. 2004-10.
87. **McGrath, B. J., Newman, M. C., Lawson, B. D., & Rupert, A. H. (2015). An Algorithm to Improve Ground-Based Spatial Disorientation Training. Proceedings of the American Institute of Aeronautics and Astronautics, Virginia Beach, 7 Jan., 9 pages.**
88. **McGrath B. J., Mortimer B. J., French J., & Drakunov S. (2016) "Mathematical Multi-Sensory Model of Spatial Orientation" Invited Paper. Proceedings, American Institute of Aeronautics and Astronautics conference on Guidance, Navigation and Control, San Diego, CA, USA, 4 - 8 January.**
89. Melvill Jones, G., & Young, L. R. (1978). Subjective detection of vertical acceleration: a velocity-dependent response? Acta oto-laryngologica, 85(1-6), 45-53.
90. Melvill Jones, G., Rolph, R., & Downing, G. H. (1978). Human subjective and reflex responses to sinusoidal vertical acceleration (DRB Aviation Medicine Research Unit Reports {Vol. V}). Montreal:McGill University and Ottawa: Defence Research Board, 256-70.
91. Merfeld, D. M. (1995). Modeling human vestibular responses during eccentric rotation and off vertical axis rotation. Acta Oto-Laryngologica, 115(S520), 354-359.
92. **Merfeld, D. M. (1990). Spatial Orientation in the Squirrel Monkey: An Experimental and Theoretical Investigation. Ph.D. Thesis, Man-Vehicle Laboratory, Cambridge, Massachusetts: Massachusetts Institute of Technology.**
93. Merfeld, D. M., & Zupan, L. H. (2002). Neural processing of gravitoinertial cues in humans. III Modeling tilt and translation response. Journal of Neurophysiology, 87(2):819-833.

94. Merfeld, D. M., Young, L. R., Oman, C. M., & Shelhamer, M. J. (1993). A multidimensional model of the effects of gravity on the spatial orientation of the monkey. Journal of Neurophysiology, 3(2):141-161.

95. Merfeld, D. M., Zupan, L. H., & Gifford, C. A. (2001). Neural processing of gravitoinertial cues in humans. II. Influence of the semicircular canals during eccentric rotation. Journal of Neurophysiology, 85(4):1648–1660.

96. Merryman R. F., & Cacioppo A. J. (1997) The optokinetic cervical reflex in pilots of high-performance aircraft. Aviat Space Environ Med. Jun; 68(6):479-87.

97. Mittelstaedt, H. (1995). Evidence of Somatic Graviception from New and Classical Investigations. Acta Otolaryngologica 186-187.

98. Mittelstaedt, M. L., & Glasauer, S. T. E. F. A. N. (1991). Idiothetic navigation in gerbils and humans. Zool. Jb. Physiol, 95(427-435).

99. Money K. E., Aitken J. F., Bondar R. L., Chevrier W. T., Garneau M., Kereliuk S., Maclean S., & Thirsk R. (1990). Experimental production of pilot disorientation in a t33 aircraft. Aviation Space & Environmental Medicine. 61(5): 478

100. Newman, L. (2012). Thirty Years of Airline Loss of Control Mishaps. Proceedings, American Institute of Aeronautics and Astronautics, 1-11, 15 August. Minneapolis, MN.

101. Newman, M. C. (2009). A Multisensory Observer Model for Human Spatial Orientation Perception. S.M. Thesis, Man-Vehicle Laboratory, Cambridge, Massachusetts: Massachusetts Institute of Technology.

102. Newman, M. C., Lawson, B. D., McGrath, B. J. & Rupert, A. H. (2014). Perceptual Modeling as a Tool to Prevent Aircraft Upset Associated with Spatial Disorientation. AIAA Guidance, Navigation, and Control Conference. January 13-17, National Harbor, Maryland.

103. Newman, M. C., Lawson, B. D., Rupert, A. H., & McGrath, B. J. (2012). The role of perceptual modeling in the understanding of spatial disorientation during flight and ground-based simulator training. Proceedings of the American Institute of Aeronautics and Astronautics, 15 Aug., Minneapolis, MN.

104. Newman, M. C., Lawson, B. D., Rupert, A. H., Thompson, L. B. & McGrath, B. J. (2014). The orientation modeling system (OMS): description of the user interface. USAARL Tech Report No 2014-09.

105. Oman, C. M. (1982). A heuristic mathematical model for the dynamics of sensory conflict and motion sickness. Acta Otolaryngologica (supplement) 392:1-44.

106. Oman, C. M., & Cullen, K. E. (2014). Brainstem processing of vestibular sensory exafference: implications for motion sickness etiology. Experimental Brain Research, 232(8):2483-2492.

107. Onur, C. (2014). Developing a Computational Model of the Pilot's Best Possible Expectation of Aircraft State Given Vestibular and Visual Cues.

108. Onur, C., Bozan, A, & Pritchett, A. (2014). Computational modeling to predict pilot's expectation of the aircraft state given vestibular and visual cues. Systems and Information Engineering Design Symposium (SIEDS), 271-276, 25 April, Charlottesville, VA.

109. Otakeno S., Matthews R. S., Folio L., Previc F. H., & Lessard C. S. (2002). The effects of visual scenes on roll and pitch thresholds in pilots versus nonpilots. Aviat Space Environ Med. Feb; 73(2):98-101.

110. Pancratz D. J., Bomar J. B. Jr., & Raddin J. H. Jr. (1994). A new source for vestibular illusions in high agility aircraft. Aviat Space Environ Med. Dec; 65(12):1130-3.

111. Pommellet, P. E. (1990). Suboptimal estimator for the spatial orientation of a pilot. S.M. Thesis, Man-Vehicle Laboratory, Cambridge, Massachusetts: Massachusetts Institute of Technology.

112. Repperger, D. W., & W. B. Albery. (1997). Patent 5,629,848. Spatial Disorientation Detector. The Unites States of America as Represented by the Secretary of the Air Force, assignee.

113. Research & Technology Organisation (RTO). (2002). Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures. RTO Meeting Proceedings 86. North Atlantic Treaty Organisation.

114. Robinson, D. A. (1977). Vestibular and optokinetic symbiosis: an example of explaining by modeling. In: Baker R, Berthoz A, eds. Control of gaze by grain stem neurons, developments in neuroscience, Vol. 1. Amsterdam: Elsevier/North-Holland Biomedical Press, 49-58

115. Rogers, R. O., Boquet, A., Howell, C., & DeJohn, C. 2007. Preliminary Results of an Experiment to Evaluate Transfer of Low-Cost, Simulator-Based Airplane Upset-Recovery Training. Embry-Riddle Aeronautical University and FAA Civil Aerospace Medical Institute DOT/FAA/AM-07/27, Daytona Beach, FL and Oklahoma City, OK.

116. Schone, H. (1964). On the Role of Gravity in Human Spatial Orientation. Aerospace Medicine 35:764-772.

117. Selva, P., & Oman, C. M. (2012). Relationships between Observer and Kalman Filter models for human dynamic spatial orientation. Journal of Vestibular Research, 22:69-80

118. Shillinger G. L. Jr., Von Baumgarten R. J., & Baldrighi G. (1973) The gravity reference response, the rotation sensation, and other illusory sensations experienced in aircraft and space flight. Space Life Sci. Sep-Dec; 4(3):368-90.

119. Small, R. L., Wickens, C. D., Keller, J. W., Oman, C. M., Young, L. R., Jones, T. D., & Brehon, M. (2008). Modeling and mitigating spatial disorientation in low g environments: Year 1 report (under NASA contract NCC 9-58-511, NSBRI project# SA01302, Alion project# 4658). Boulder, CO: Alion Science & Technology Corp. [Available from the first author at rsmall@ alionscience. com.].

120. Small, R. L., Keller, J. W., Wickens, C. D., Socash, C. M., Ronan, A. M., & Fisher, A. M. (2006). Multisensory integration for pilot spatial orientation. Micro Analysis and Design, Boulder Colorado Report A253074.

121. Small, R. L., Oman, C. M., Wickens, C. D., Keller, J. W., Curtis, B., Jones, T. D., & Brehon, M. (2011). Modeling and mitigating spatial disorientation in low-G environments: Final Report. (NSBRI Project # SA-01302).

122. St. George, R. J., Day, B. L., & Fitzpatrick, R. C. (2011). Adaptation of vestibular signals for self-motion perception. The Journal of Physiology, 589(4), 843-853.

123. Stenger B., Thayananthan A., Torr P. H., & Cipolla R. (2006) "Model-based hand tracking using a hierarchical Bayesian filter", IEEE Transactions on Pattern Analysis and Machine Intelligence, 28(9):1372-84.

124. Sullivan, J., Yang, J. H., Day, M., & Kennedy, Q. (2011). Training simulation for helicopter navigation by characterizing visual scan patterns. Aviation, space, and environmental medicine, 82(9), 871-878.

125. Todd, N. P., Rosengren, S. M., & Colebatch, J. G. (2009). A utricular origin of frequency tuning to low-frequency vibration in the human vestibular system? Neuroscience letters, 451(3), 175-180.
126. Tokumaru, O., Kaida, K., Ashida, H., Mizumoto, C. & Tatsuno, J. (1998). Visual influence on the magnitude of somatogravic illusion evoked on advanced spatial disorientation demonstrator. Aviation, Space, and Environmental Medicine, 69(2), pp.111-116.
127. Tormes, F. R. & Guedry F. E. Jr., (1974). Disorientation phenomena in naval helicopter pilots (No. NAMRL-1205). NAVAL AEROSPACE MEDICAL RESEARCH LAB PENSACOLA, FL.
128. Tribukait, A., & Eiken, O. (2006). Semicircular canal influence on the visually perceived eye level during gondola centrifugation. Aviation, space, and environmental medicine, 77(5), pp.500-508.
129. Tribukait, A., & Eiken, O. (2012). Flight experience and the perception of pitch angular displacements in a gondola centrifuge. Aviation, space, and environmental medicine, 83(5), pp.496-503.
130. Ungs, T. J. (1989). The occurrence of the vection illusion among helicopter pilots while flying over water. Aviat Space Environ Med. Nov; 60(11):1099-101.
131. Vingerhoets, R. A. A., Van Gisbergen, J. A. M., & Medendorp, W. P. (2007). Verticality perception during off vertical axis rotation. Journal of Neurophysiology, 97(5):3256-3268.
132. Wearne S., Raphan T., & Cohen B. (1999). Effects of tilt of the gravitoinertial acceleration vector on the angular vestibule-ocular reflex during centrifugation. J Neurophysiol 81: 2175–2190
133. Young L. R. (1970). On visual vestibular interactions. Proc. 5th Symposium of the role of the vestibular organs is space exploration. NASA SP 314:205-210.
134. Young, L. R. (2011). Optimal estimator models for spatial orientation and vestibular nystagmus. Experimental brain research, 210(3-4), 465-476.
135. Young, L. R., & Oman, C. M. (1970). Section of Instrumentation: Modeling Adaptation in Human Semicircular Canal Response to Rotation. Transactions of The New York Academy of Sciences, 32(4 Series II), 489-494.
136. Zupan, L. H., Merfeld, D. M., & Darlot, C. (2002). Using sensory weighting to model the influence of canal, otolith and visual cues on spatial orientation and eye movements. Biological Cybernetics 86(3): 209-230.

Department of the Army
U.S. Army Aeromedical Research Laboratory
Fort Rucker, Alabama, 36362-0577
www.usaarl.army.mil

U.S. Army Medical Research and Materiel Command